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Central Asian rivers under climate change: Impacts assessment in eight representative catchments

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ABSTRACT

Study region: Eight river catchments within Central Asia.
Study focus: The limited amount of water resources is already an issue in the Central Asian region, and climate change may be crucial for water availability and development of countries in the region. This study investigates potential climate change impacts on water resources in Central Asia to the end of the century by focusing on eight river catchments with diverse natural conditions located in different countries. The eco-hydrological model SWIM was setup, calibrated and validated for all selected catchments under study. Scenarios from five bias-corrected GCMs under Representative Concentration Pathways 4.5 and 8.5 were used to drive the hydrological model.
New hydrological insights for the region: The results show an increase of mean annual temperature in all catchments for both RCPs to the end of the century. The projected changes in annual precipitation indicate a clear trend to increase in the Zhabay and to decrease in the Murghab catchments, and for other catchments, they were smaller.
The projected trends for river discharge are similar to those of precipitation, with an increase in the north and decrease in the south of the study region. Seasonal changes are characterized by a shift in the peak of river discharge up to one month, shortage of snow accumulation period, and reduction of discharge in summer months.

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1. Introduction

The water resources in the Central Asian region (Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan and Turkmenistan) are mainly provided by transboundary rivers, and they play a key role in the economy of countries (Manning et al., 2018). In the mountains, for Kyrgyzstan and Tajikistan, water is the main source of electricity production (76 % of the total) by existing (operating) and planned hydropower plants ("Central Asia : Kyrgyzstan — The World Factbook," 2019; The World Bank Group, 2018). Downstream, in Uzbekistan and partly in Turkmenistan, where agriculture plays an essential role in the economy of the countries, water is demanded for crops irrigation (Russell, 2018). The share of annual freshwater withdrawals for agriculture exceeds 90 % in most Central Asian countries (except Kazakhstan) (The World Bank Group, 2019a).

The limited amount of transboundary water resources is already an issue for cooperation between the countries in the region, and information about the future changes of water availability is vitally important for sustainable development of the Central Asian countries. The unequal distribution of water resources in the region and in particular the low availability of internal renewable water resources in the downstream countries like Turkmenistan (257 m^3 per capita) and Uzbekistan (531 m^3 per capita) (The World Bank Group, 2019b), together with inefficient water use can be a source of potential conflicts in Central Asian region (Weinthal, 2006).

The natural conditions of the region are characterized by an uneven distribution of the river network, which is determined by orographic features and dominant atmospheric circulation patterns (Shults, 1965). The major part of Central Asia has a continental type of climate with strong intraannual variability (Kottek et al., 2006; Manning et al., 2018). This type of regional climate a result of its deep inland location, and the lowland area in the north, determines hot summers and cold winters in the major part of Central Asia. The lowland area is characterized by a low density of river network, low amount of precipitation, and often appears as a water dissemination zone of the river catchment through evaporation, infiltration and intensive water use for agriculture. In opposite to the lowlands, the mountainous areas due to high elevation and higher amount of precipitation have a highly dense river network and act as an accumulation zone of water resources for the whole Central Asian region (Shults, 1965). The abovementioned features indicate a prominent role of precipitation and temperature, and explain the important role of the mountainous areas, being a major source of water for river basins of Central Asia. Therefore, future climate changes will affect all countries in the region, which are highly dependent on water resources.

The problem of climate change impact is crucial for the future development of the Central Asian countries (Kazakhstan, Kyrgyzstan, Uzbekistan, Tajikistan and Turkmenistan). Up to now, there has been a limited amount of studies that looked into ongoing and future changes of climate in Central Asia and their impacts on water resources (Hijioka et al., 2014; Saibnazarova, 2015; Agaltseva et al., 2011; Savitskiy et al., 2008), which significantly limits understanding of future changes for specific regions.

Fig. 1. Eight river catchments under study in Central Asia.

Table 1
Main characteristics of the catchments under study (AF – Afghanistan, KG – Kyrgyzstan, KZ – Kazakhstan, TJ – Tajikistan, TM – Turkmenistan, UZ – Uzbekistan,).

Basin	Country	Modelled area, km^2	Min elev., m	Mean elev., m	Max elev., m	Annual P, mm	Mean annual T, C	Mean T, C (JJA)	Discharge, m3/s	Gauge name	Period for estimation of climate parameters
Zhabay	KZ	8530	274	300	725	426	2.9	19.1	9.4	Atbasar	2000–2013
Bukhtarma	KZ	10,700	437	1539	4480	612	−3.2	12.8	203	Lesnaya-pristan	2000–2013
Aspara	KZ, KG	1160	531	1557	4074	440	6.1	18.2	2.37	–	1961–2001
Isfara	TJ, KG	3200	634	2266	5007	440	6.4	17.5	14	Tash-kurgan	1961–2001
Zeravshan	TJ, UZ	10,200	879	2943	5120	451	3.8	14.8	155.8	Dupuli	1979–2013
Tupalang	TJ, UZ	2630	451	1786	4364	405	7.1	17.4	33.5	Obizarang	1960–2001
Kafirnigan	TJ	3216	896	2673	4368	677	5.3	16.2	95.5	Chinor	1979–2013
Murghab	AF, TM	35,963	335	1694	3931	308	12.8	24.3	51.2	Taghtabazar	2000–2013

Most of the studies confirm a general temperature increase in the Central Asian region during the 20th century with an acceleration since the 1970s. The mean annual temperature raised from 0.18 to 0.42 °C per decade during the last 60 years, and at the same time, no clear trends were found for annual precipitation (Hijioka et al., 2014).

The future changes of mean annual temperature over Central Asia are projected to be higher compared to the global mean, with an increase by more than 5 °C to the end of the century and up to 6.5 °C in summer months under RCP 8.5 (Reyer et al., 2015; White et al., 2014).

The projected changes in precipitation have no clear trend. Several studies for the Amu Darya basin suggest an uncertain or small increasing tendency. For example, in the study of Hagg et al. (2013) for the upper Amu Darya basin show a small increase from 3 to 4% by 2050. Also, the results of Gan et al. (2015) for the Naryn catchment (a tributary of the Syr Darya) the annual precipitation is projected to change from -7.4 % to +2.3 % under different climate projections by the end of the century.

As a result of the expected temperature increase and glaciers reduction, a slight decrease in mean annual river discharge is projected for the Central Asian region (Gan et al., 2015; Hagg et al., 2013; Reyer et al., 2015; White et al., 2014). Seasonal changes of river discharge are characterized by a shift of timing of peak runoff to an earlier period, as was shown for the Naryn catchment (Gan et al., 2015), for the upper Amu Darya basin (Hagg et al., 2013; Immerzeel et al., 2012) and for the Chu catchment (Changkun et al., 2015).

In general, there are not many studies dedicated to climate change impact assessment on water resources in the region. The majority of them are for only one river catchment so that it is not possible to see a pattern for the whole region.

The aim of the current study is the assessment of the climate change impacts on water availability in the selected river basins in Central Asia by employing the eco-hydrological model SWIM, set up, calibrated and validated for each of the considered river basins, driven by bias-corrected GCMs (Global Climate Models) under two RCPs (Representative Concentration Pathway) scenarios until the end of the century. The selected catchments across Central Asia were chosen to cover the whole region, representing different climate conditions and different countries. In order to get more robust trends of future changes, it was decided to use an ensemble of five bias-corrected GCM scenarios under RCP 4.5 and RCP 8.5.

2. Study area

For assessment of climate change impacts on water resources, eight pilot hydrological river basins, situated within six Central Asian countries, were selected (Fig. 1). The river basins are located in different natural zones, have different sizes and different flow regimes (nival, nivo-glacial or glacio-nival).

The Zhabay and Bukhtarma river catchments, which belong to the Ertis river basin, are located in the northern part of the region within Kazakhstan. Both catchments have low mean annual temperatures: 2.9 °C in the Zhabay catchment and -3.2 °C in the Bukhtarma catchment. The next five catchments are all located in the central part of the region: three of them belong to the Amu Darya basin (Kafirnigan, Tupalangdarya (Tupalang) and Zeravshan), one to Syr Darya (Isfara) and one to the Chu river basin (Aspara). All catchments originate in the high mountains (except Zhabay) and are fed mainly by snow and glaciers melt (CAREC, 2014a, b). The most southern pilot catchment is Murghab, which originates in the highlands of Afghanistan and flows into the Karakum Desert. This catchment has the driest and the hottest climate conditions among our river catchments under study. The main characteristics of the catchments are presented in Table 1.

The range of climate conditions in the case study area is reflected by the difference in mean annual temperatures, which is 16 °C between the Bukhtarma (-3.2 °C) and Murghab (12.8 °C) catchments. The seasonal distribution of precipitation also has some regional aspects depending on the catchment. In the Zhabay and Bukhtarma river catchment, the highest precipitation occurs in summer (July), in the Murghab – in February – March and in the rest of the catchments - during the spring months.

Elevation and geographical aspect have a significant influence on the hydrological cycle and conditions of the river catchments. For example, Kafirnigan river originates on the Hissor range, where borders with Zeravshan, but the Kafirnigan catchment has a southerly aspect causing higher temperature and precipitation. The Kafirnigan has a nivo-glacial flow regime. The Zeravshan catchment has a northerly aspect and comparably less precipitation, lower mean temperature, and glacio-nival regime of the river flow. On the other hand, within the Zhabay catchment, which is located in the north of the region, the range between minimum and maximum altitudes within the catchment does not exceed 500 m. Nevertheless, all catchments have strong river discharge seasonality with high flows in spring or summer, depending on the main river flow regime (Shults, 1965).

According to the natural and socio-economic conditions, water use in the region is in high demand. After the Soviet Union collapsed, the designed water infrastructure system that focused on serving the cotton production and was an economic basis of the region became ineffective due to new economic priorities of newly independent countries. New water management national plans of Central Asian countries conflict with each other (Russell, 2018; Weinthal, 2006). Due to low amount of precipitation in the major parts of Central Asia (The World Bank Group, 2016), water is used mainly for irrigation in the agriculture sector, and upstream situated Tajikistan and Kyrgyzstan aim to develop their hydroelectrical potential through the construction of new dams (Russell, 2018).

3. Methodology

3.1. SWIM model description

The Soil and Water Integrated Model (SWIM) is a continuous-time, semi-distributed process-based eco-hydrological model. The model is based on previously developed models SWAT and MATSALU and integrates hydrological processes, vegetation growth, sediment transport and nutrient cycling (N and P). SWIM uses a three-level spatial disaggregation scheme: basin — sub-basins — hydrotopes (or hydrologic response units, HRUs). The model operates on a daily time step and is driven by precipitation, temperature (average, maximum and minimum), air humidity, wind speed and solar radiation. Also, SWIM requires a land-use map, a digital elevation model, a soil map, vegetation and soil parameters as input, more detailed information on that can be found in Krysanova et al. (2000).

The model was successfully applied in numerous catchments at different scales and with different natural conditions within Europe, Asia, America and Africa (Didovets et al., 2019; Koch et al., 2013; Liersch et al., 2018; Lobanova et al., 2018).

3.2. Model setup, calibration, and validation

To set up the SWIM model, a Digital Elevation Model (DEM), soil map with parameterization, land use map, and climate data are needed as input. Due to the lack of local data covering the pilot regions, it was necessary to retrieve them from the global databases.

A DEM is available over the entire globe from the Shuttle Radar Topography Mission (SRTM) Consultative Group for International Agricultural Research (CGIAR) Database. This dataset is available on the CGIAR website (CGIAR-CSI, 2017). It was initially produced by NASA and has a resolution of 90 × 90 m at the equator.

The Globeland30 dataset contains land cover information over the entire globe with the 30 m resolution data, also covering the pilot areas of this study. The dataset was carried out by the Ministry of Science and Technology of China, and the mapping product was derived from remote sensing images in 2010. The dataset has ten land cover types: cultivated land, forest, grassland, shrubland, wetland, water bodies, tundra, artificial surfaces, bare land, and permanent snow and ice (Chen et al., 2014; National Geomatics Center of China, 2014).

Soil information with a resolution of 1000 × 1000 m from the Harmonized World Soil Database FAO70 (FAO/IIASA/ISRIC/ISSCAS/JRC, 2012; Panagos et al., 2012) created by the Food and Agriculture Organization of the United Nations is available over the entire globe. This database does not include all soil parameters needed for SWIM, but the missing parameters were estimated using the method of pedotransfer functions. The regional or local soil maps and parameterizations were not available for this study.

SWIM uses daily precipitation, average, minimum and maximum temperatures, solar radiation, wind speed and relative humidity as meteorological input data. Frequently, the density of meteorological stations appears to be unsatisfactory for hydrological modelling, or data series have serious gaps in records, or some needed parameters do not exist at all. Therefore, it was decided to use the WATCH Era 40 (1901–2001) re-analysis dataset (Weedon et al., 2010) or WFDEI (1979–2013) (Weedon et al., 2014) as climate input depending on the river catchment. The dataset is based on ERA-40 re-analysis (Uppala et al., 2005) and covers all needed climate fields at a spatial resolution of 0.5 degree.

The river discharge data for five river catchments (Zhabay, Bukhtarma, Zeravshan, Kafirnigan and Murghab), which are needed for the model calibration and validation, were received from the National Hydrometeorological agencies in Kazakhstan, Tajikistan, Uzbekistan and Turkmenistan. In addition, some missing observational data (Isfara and Tupalang) on discharge were retrieved from GRDC (Global Runoff Data Center) (GRDC, 56068 Koblenz, 2017). Monthly time series were available for Isfara, Zeravshan, Tupalang and Murghab, and daily – for Zhabay, Bukhtarma and Kafirnigan. For the Aspara River catchment, no observed discharge was

Table 2
Results of calibration and validation of the SWIM model for catchments under study in terms of a) NSE > 0.8 – very good, 0.7-0.8 – good, 0.5-0.7 – satisfactory b) Pbias (-5,5) – very good, (-10,-5)&(510) – good, (-15,-10)&(1015) – satisfactory c) R2 > 0.85 – very good, 0.75-0.85 – good, 0.6-0.75 – satisfactory. Green colours indicate satisfactory (light green), good (green) and very good (dark green) model performance, and yellow – not satisfactory performance. (For interpretation of the references to colour in this table, the reader is referred to the web version of this article).

Num	Basin	Period, years		NSE	Pbias	R^2
1	Zhabay	Calibration	2001-2007	0.92	10.6	0.77
		Validation	2008-2013	0.62	-21.6	0.58
2	Buhtarma	Calibration	2002-2007	0.87	-10.6	0.75
		Validation	2008-2012	0.87	-12.5	0.79
3	Isfara	Calibration	1963-1980	0.66	-4.9	0.54
		Validation	1981-1991	0.63	14.1	0.65
4	Zeravshan	Calibration	1980-1995	0.9	0.3	0.84
		Validation	1997-2013	0.83	0.8	0.82
5	Tupalang	Calibration	1961-1976	0.79	-15	0.67
		Validation	1977-1989	0.75	-1	0.73
6	Kafirnigan	Calibration	1981-1986	0.89	-3	0.86
		Validation	1987-1990	0.89	-5.3	0.81
7	Murghab	Calibration	2008-2013	0.29	11.1	0.36
		Validation				

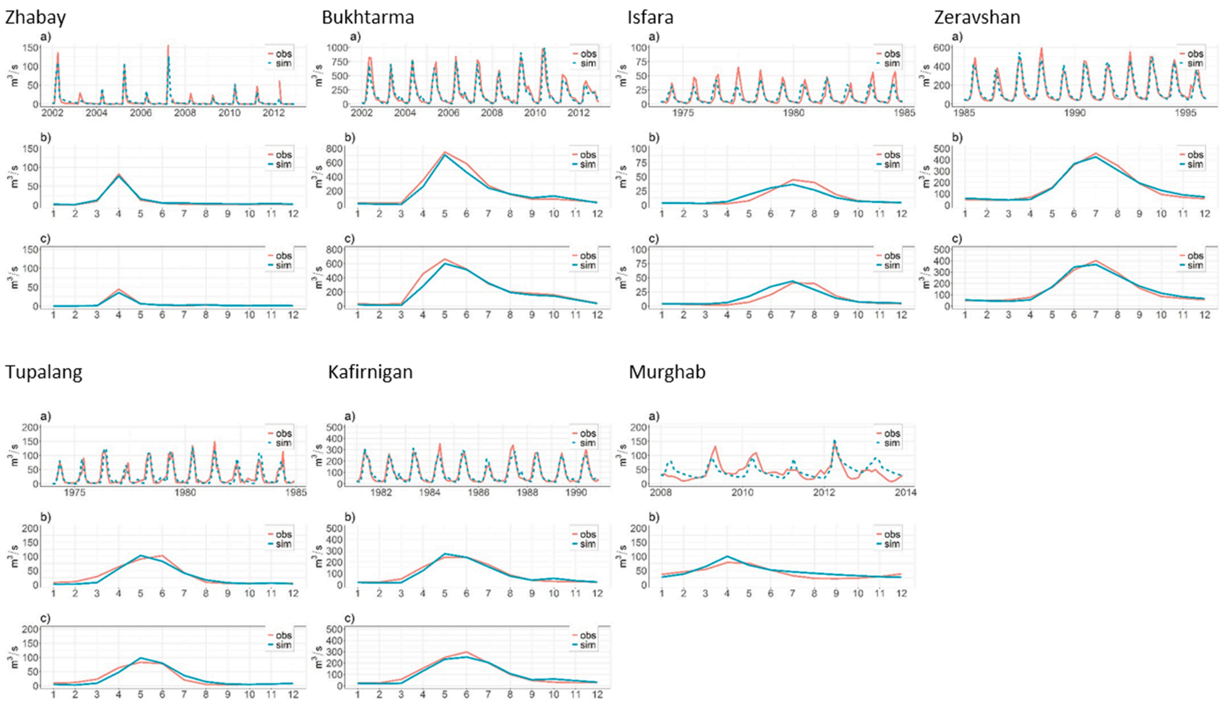

Fig. 2. Results of the SWIM model calibration and validation in seven river catchments under study: comparison of the observed and simulated river discharges with the monthly time step for the combined calibration and validation periods (a), and for the long-term mean monthly dynamics over the calibration (b) and validation (c) periods. For Murghab the comparisons are shown only for the calibration period due to data availability.

Table 3
Changes in annual mean temperature and precipitation in eight river catchments for three future periods under RCP 4.5 and RCP 8.5 in three periods to the end of the century. (Green colour indicates an increase in precipitation higher than 5%, and yellow indicates a decrease higher than 5%). (For interpretation of the references to colour in this table, the reader is referred to the web version of this article).

Catchment	RCP	delta T, C			P, %		
		Near	Mid	Far	Near	Mid	Far
Zhabay	RCP 4.5	1.6	3.2	3.9	5.9	9.6	10.6
Bukhtarma	RCP 4.5	1.4	2.7	3.3	2.3	4.9	7
Aspara	RCP 4.5	1.2	2.4	3	1.1	3.8	7.6
Isfara	RCP 4.5	1.2	2.4	3.1	0.9	1.8	1.9
Zeravshan	RCP 4.5	1.2	2.4	3.1	0.6	0.3	-0.4
Tupalang	RCP 4.5	1.2	2.4	3	0.5	-0.3	-1.7
Kafirnigan	RCP 4.5	1.2	2.5	3.2	1.3	0.8	-0.1
Murgab	RCP 4.5	1.2	2.3	3	-1	-5.9	-8.3
Zhabay	RCP 8.5	1.9	4.1	6.4	7.2	9.6	11.5
Bukhtarma	RCP 8.5	1.5	3.6	5.9	3	4.5	6.5
Aspara	RCP 8.5	1.5	3.3	5.4	-2.6	0	1
Isfara	RCP 8.5	1.5	3.4	5.6	-3.6	-1.3	-2
Zeravshan	RCP 8.5	1.5	3.3	5.5	-5.8	-2.8	-4
Tupalang	RCP 8.5	1.5	3.2	5.3	-7	-3.7	-4.6
Kafirnigan	RCP 8.5	1.6	3.5	5.7	-5.3	-1.9	-2.9
Murgab	RCP 8.5	1.5	3.3	5.5	-12.8	-10.1	-15.1

available.

Due to the lack of information about water management and operation of reservoirs, it was not possible to include water management in the model simulations. Therefore, it was decided to focus on water accumulation zones in the upper parts of the catchments that are not regulated or only moderately regulated, and have close to pristine conditions. The climate simulations for the historical period were not compared to observations due to lack of observed data for the mountainous areas. Nevertheless, as already have been mentioned, GCMs were bias-corrected to reanalysis data in advance in order to decrease the deviations. Also, the study by Lobanova et al. (2017) included such a comparison for a part of our study area, which showed low deviations of the ISIMIP simulations for the historical period in the Isfara and Aspara catchments.

3.3. Climate scenarios

For this study, all five CMIP5 GCM simulations adapted for the project ISIMIP ("ISIMIP - The Inter-Sectoral Impact Model Intercomparison Project," 2019) were chosen: GFDL-ESM2M, HadGEM2-ES, IPSL-CM5A-LR, MIROC-ESM-CHEM, NorESM1-M. The projections were previously bi-linearly interpolated to a 0.5-degree resolution and bias-adjusted to the WATCH ERA40 data (for the period from 1 January 1960 to 31 December 1999). The bias-adjustment approach, used for the ISIMIP, assumes preservation of the long-term trend of the simulated climate variables (temperature, radiation, precipitation, wind). More detailed information about the bias correction method can be found in Hempel et al., 2013.

In this study, it was decided to include the moderate and high emission scenarios until the end of the 21st century. For this purpose, all projections were run under the RCP 4.5 (moderate emissions scenario) and RCP 8.5 (high emissions scenario) concentration pathways for the period from 1950 to 2100.

3.4. Data analysis

To analyse the projected changes in climate parameters and river discharge, three future periods (2011–2040, 2041–2070, 2070–2100, later named as Near, Mid and Far future periods) were considered and compared with the reference period of 1981–2010.

The multi-model median was used to calculate 30-years average values of climate and river discharge variables for each period. Changes in temperature were considered in absolute values (°C), and precipitation changes were estimated and presented as relative values (%).The river discharge was simulated with the SWIM model calibrated and validated for each basin in advance, and driven by five GCMs under RCP4.5 and RCP8.5 scenarios until the end of the century. For the analysis of future changes, the simulations were divided in 30-year periods and compared to those in the reference period. More information and results are presented in Section 4.2.

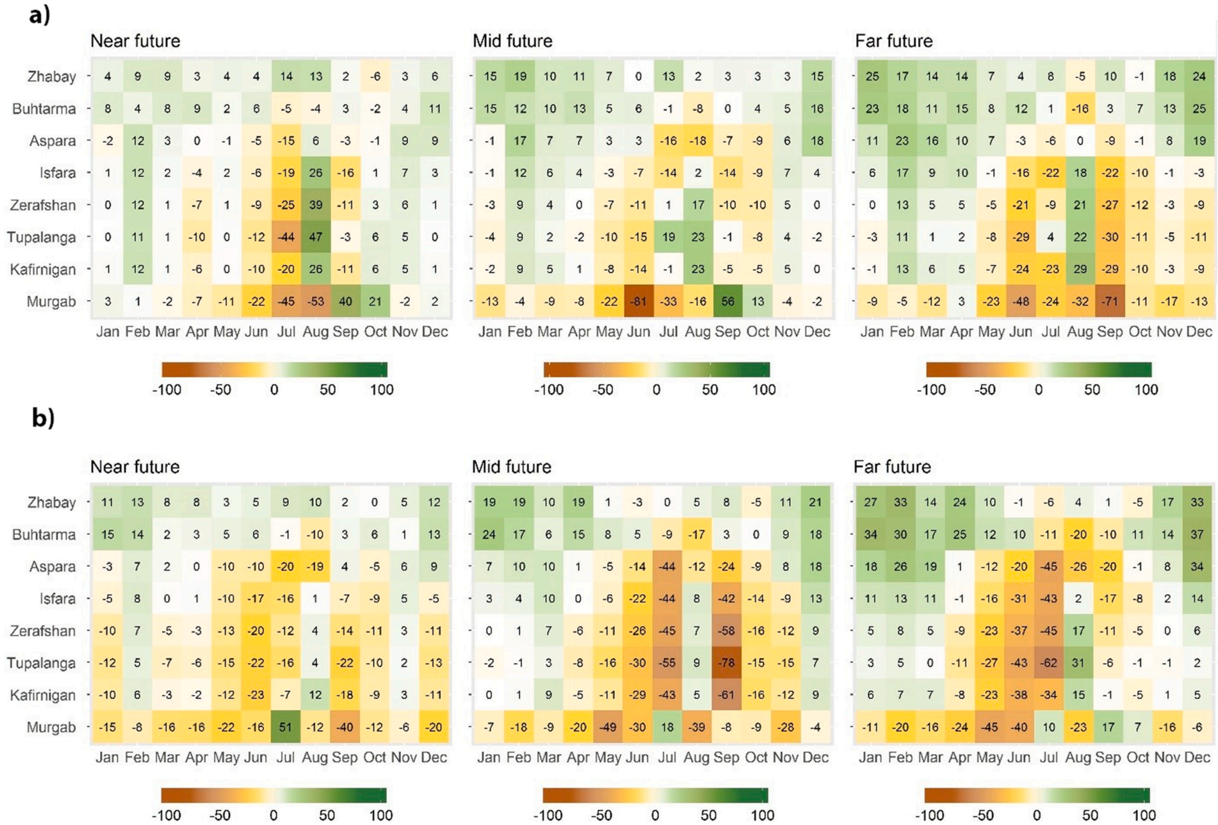

Fig. 3. Changes (%) in the long-term mean monthly precipitation for three future periods in comparison to the reference period under RCP 4.5 (a) and RCP 8.5 (b).

4. Results

4.1. Calibration and validation

The results of calibration and validation of the SWIM model in terms of criteria of fit, together with the graphs comparing the observed and simulated river discharges are presented in Table 2, Fig. 2 for seven river catchments under study. The SWIM model was manually calibrated for all river basins under study (except for the Aspara basin, due to missing data). Due to differences in discharge data availability: daily or monthly (and no data for the Aspara), and different time periods of available data, the model was calibrated and validated for each river catchment separately.

The observed time series for the Murghab river catchment were limited to 6 years only, which were used for the model calibration, and validation was omitted. The observation data for the Bukhtarma, Kafirnigan and Zhabay catchments were available with daily time step (Appendix 1), and the Isfara, Zeravshan and Tupalang catchments with the monthly time step. All seven catchment were calibrated and validated with monthly time step. For the Aspara catchment, the calibration parameters of the Isfara river were used (conditions in both are similar).

During the calibration, the most important parameters for all study regions were related to snow and routing processes. Also, for the mountainous catchments with glaciers, a simple glacier module was used, which helped to improve the performance of the model there. The glacier module uses a degree-day method to simulate glacier melt and glacier water accumulation on a daily basis. The annual mass balance is calculated at the hydrotope level (Huang et al., 2013). The ranges of the major model parameters used for the SWIM model calibration across study catchment are presented in Appendix 2.

The SWIM model considers input climate parameters as being constant at the sub-basin scale. In order to downscale the large scale climate input, in the high mountainous areas, additional adjustment of temperature and precipitation with altitude was applied during the calibration process at the hydrotope level. This approach (integrated into the model) assumes linear dependencies on elevation.

To estimate the model performance, the NSE, Pbias and R^2 criteria were calculated for the calibration and validation periods. The obtained calibration results for the majority of catchments correspond from "satisfactory" to "very good" (according to (Moriasi et al., 2015)). The lowest NSE value was obtained for the Murghab river catchment. It can be explained by extensive water management activities upstream the gauging station, which were not represented in the model due to missing data, and lack of other local input data.

Table 4
Changes in mean annual runoff for three future periods in comparison to the reference period under RCP 4.5 and RCP 8.5. (Green colour indicates an increase higher than 10 %, and yellow indicates a decrease higher than 10 %). (For interpretation of the references to colour in this table, the reader is referred to the web version of this article).

Basin	RCPs	deviation, %		
		near	mid	far
Zhabay	RCP 4.5	7.5	21.6	30.6
Bukhtarma	RCP 4.5	0.8	2.1	4.6
Aspara	RCP 4.5	-2.9	0	5.9
Isfara	RCP 4.5	-6.7	-12.4	-15.2
Zeravshan	RCP 4.5	1.2	-0.6	-2.4
Tupalang	RCP 4.5	-1.5	-3.4	-5.8
Kafirnigan	RCP 4.5	0.3	-0.8	-2.3
Murghab	RCP 4.5	-2	-26.5	-26.1
Zhabay	RCP 8.5	11.1	26.2	32.5
Bukhtarma	RCP 8.5	2.5	0.8	0.6
Aspara	RCP 8.5	-8.6	-8.6	-2.9
Isfara	RCP 8.5	-11.3	-19.8	-30.2
Zeravshan	RCP 8.5	-5.7	-5.3	-7.4
Tupalang	RCP 8.5	-10.8	-8.4	-10.8
Kafirnigan	RCP 8.5	-6.7	-4.2	-6.1
Murghab	RCP 8.5	-33.7	-28.6	-40.4

4.2. Analysis of changes in precipitation and temperature

According to climate scenarios from the five ISIMIP models, the annual mean temperature (T) increases in all catchments under both RCP scenarios from 1.2 °C in the Near future up to 6.4 °C in the Far future, with higher changes under RCP 8.5 compared to RCP 4.5. The highest T rise is projected for the Zhabay catchment with up to 3.9 °C under RCP 4.5 and up to 6.4 °C under RCP 8.5 by the end of the century. For other catchments, the projected changes are within the range of 3 °C – 3.3 °C under RCP 4.5 and 5.3 °C – 5.9 C° under RCP 8.5 in the Far future period (Appendix 3 and Table 3).

The projected changes in annual precipitation are qualitative different between the eight regions as in temperature, with some increase in the northern and decrease in the southern and central catchments. The Zhabay catchment has a distinct trend towards a moderate increase in all periods and RCPs up to 11.5 % by the end of the century. Similar tendency but with lower magnitude changes is projected for the Bukhtarma and Aspara catchments under RCP 4.5. A clear negative trend in annual precipitation is projected for the most southern catchment – Murghab – under both RCPs, up to 15.1 % under RCP 8.5 in the far future. Only minor changes are projected for the rest of the catchments in the central part of the study region.

The projected changes in the long-term monthly mean precipitation for the catchments are shown in Fig. 3. As a general pattern, precipitation increases in most cases in winter and decreases in summer, and this trend is more pronounced under RCP8.5 (higher warming). The projected results for the Zhabay and Bukhtarma catchment show an increase of precipitation in the majority of periods and months under both RCPs, except some late summer and early fall months. The greatest changes are expected in winter and spring months by the end of the century and can reach up to 37 %. The mean monthly changes for the period from November to April show an increase by 18 % under RCP 4.5 and 25 % under RCP 8.5. The rest of the catchments, located in the central and southern parts, except Murghab, have some tendency to an increase in precipitation in February-March, and a decrease in summer months (except August) under RCP 4.5. Under RCP 8.5 the projected precipitation decrease is higher and also extends to autumn months. Similar to the annual mean changes, the highest negative monthly changes during the year are projected for the Murghab catchment under both RCPs.

In general, the highest decreases are expected for catchments in the central part in July and September in the mid future, and in June-July in the far future under RCP 8.5, as well as for the Murghab in summer months (all periods, both RCPs).

4.3. Projected impacts on river discharge

Changes in the mean annual discharge for three future periods in the eight river catchments under study are presented in Table 4. The biggest positive changes in all periods are projected for the Zhabay River catchment (north), with more than 30 % increase by the end of the century under both RCPs. Changes in river discharge for the Bukhtarma catchment are positive, but negligibly small (< 5%).

The highest negative changes in the mean annual discharge are projected for the Murghab catchment (south) for both RCPs in all periods, reaching 40 % under RCP 8.5 in the far future. According to the projections, river discharge will also decrease in the Isfara catchment in all three periods in both RCPs, especially under RCP 8.5, where the decrease is higher than 30 % in the Far future period. The simulated strong negative changes in discharge in these cases can be explained mainly by an increase of mean annual temperature (Table 3), which is projected to rise by more than 5 °C under RCP 8.5 by the end of the century. Changes in the other catchments are negligible (< 5%) or small negative (from -5 to -11 %) under both RCPs.

The simulated long-term mean monthly discharge in the reference period and in three future periods is presented in Figs. 4 and 5for

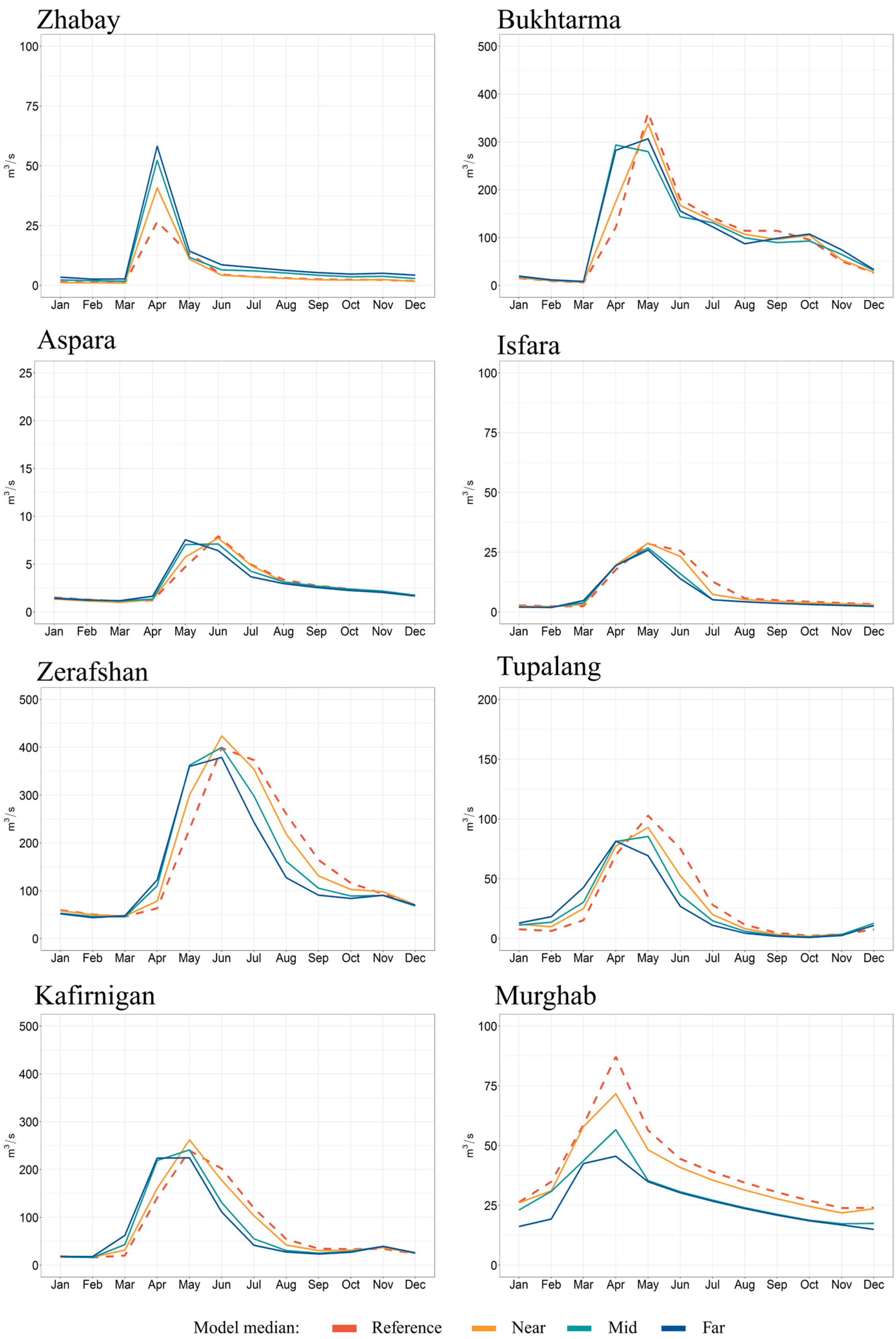

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Fig. 4. Multi-model medians of monthly river discharge for three future periods compared to the reference period under RCP 4.5.

eight basins under two RCPs. Only the medians from the multi-model runs (SWIM driven by five GCMs) are shown here.

The projections of the long-term monthly mean river discharge show a strong increase in the Zhabay catchment (north) in the mid and far future periods under both RCPs, except May, when a decrease by 12 % is projected under RCP 4.5. In the near future, the river discharge will slightly decrease in the majority of months under RCP 4.5.

A decreasing trend can be anticipated in the Murghab catchment (south). The long-term mean monthly river discharge is decreasing in all periods under both RCPs during the whole year. The highest decrease is projected for the Far future period under RCP 8.5 when river discharge decreases by more than 40 % in all months.

For the Bukhtarma catchment (north) a small increase from November to March is projected, a strong increase in April and a decrease from May to September in all three periods under both RCPs. In the Aspara, Isfara and Zeravshan catchments, with the exception of small to moderate increase in the spring months related to peak shifts, river discharge is projected to decrease in the rest of the season in all three periods under both RCPs. The highest decrease is in summer months and can reach up to 60 % (Figs. 4 and 5).

Results for the Tupalang and Kafirnigan show a similar tendency with an increase of discharge in spring months and decrease in summer and early fall months. However, the increase in discharge in winter months in the Tupalang catchment is relatively higher under RCP 4.5 compared to RCP 8.5.

A clear tendency of shifting peaks in river discharge to an earlier period (up to one month) as a result of temperature increase and more intensive snowmelt processes has been found for six catchments under study, except Zhabay and Murghab. The shifts are larger under RCP 8.5 compared to RCP 4.5 (Figs. 4, 5 and Appendix 4). Also, there is a clear pattern of decrease in river discharge from June to September for all catchments, in all future periods under both RCPs, except Zhabay.

Spreads in the model outputs in future periods for the majority of catchments are on the same level as in the reference period under both RCPs (Figs. 6 and 7). However, for the Zeravshan, Kafirnigan and Tupalang, the uncertainty is increasing to the end of the century. The Murghab catchment is characterized by a strong interannual variability of annual discharge driven by different scenarios in all periods and under both RCPs.

We also analyzed changes in snow cover in the catchments under climate warming. As an example, Fig. 8 shows the mean monthly snow cover in the Kafirnigan catchment in winter months for the reference (1981–2010) and far future period (2071–2100) under RCP 8.5. In all three months, the snow cover is projected to decline. In Fig. 8 also, the mean annual snowmelt from 1950 to 2100 is displayed, showing a reduction to the end of the century. This can be explained by the projected temperature rise in the cold season and a reduction of snow accumulation processes.

5. Discussion and comparison of the obtained results with other studies

Our results based on GCMs show an increase of annual mean temperature in all catchments under study until the end of the century. Temperature increase under RCP 8.5 in some basins can be higher than 6 °C; Our findings are also confirmed by other studies (Gan et al., 2015; Ozturk et al., 2017). The temperature increase leads to a reduction of snow accumulation during the cold season and higher evapotranspiration during summer. In some regions, that kind of changes can be beneficial for agriculture production due to prolongation of vegetation period (Lobanova et al., 2021). On the other hand, an increase of potential evapotranspiration as a result of temperature rise with the same level of actual evapotranspiration, which is limited by water availability, could lead to an increase of water demand in the region.

Shortage of snow accumulation period during the year and reduction of water volume accumulated as snow means less water available during vegetation period and irrigation in general. Clear trend in temperature increase in the region with the snow and glacier fed rivers plays a big role for potential changes of river runoff. In the majority of the catchments under study, notable seasonal changes in river discharge were found. A shift of the peak discharge up to one month earlier was projected, which was also confirmed by other studies (Gan et al., 2015; Hagg et al., 2013; Reyer et al., 2015).

In general, regarding projected changes, the case study basins can be divided into three groups: north, south and central. In the north, in Kazakhstan, there is a clear trend to increase in temperature and precipitation, as well as river discharge during the year. This group is represented by the Zhabay and partly the Bukhtarma catchments. In the central part, all mountainous catchments have clear seasonal changes in river discharge, and shift of the peak discharge to an earlier period, as mentioned above. In the south in the arid zone, within Afghanistan and Turkmenistan, there are opposite, decreasing trends in precipitation and river discharge in all months, in all three future time periods and under both climate projections, as demonstrated for the Murghab River catchment case study.

The projected results on climate change impacts are associated with uncertainties due to uncertainty of climate projections, the uncertainty of input data based on observations and also due to water management in the region of Central Asia which may alter river discharge and influence the simulated results. The highest uncertainty in impact assessment usually results from climate models (Vetter et al., 2017), and improvements in this direction together with adjustments to specific regional conditions can help to reduce the uncertainty in future.

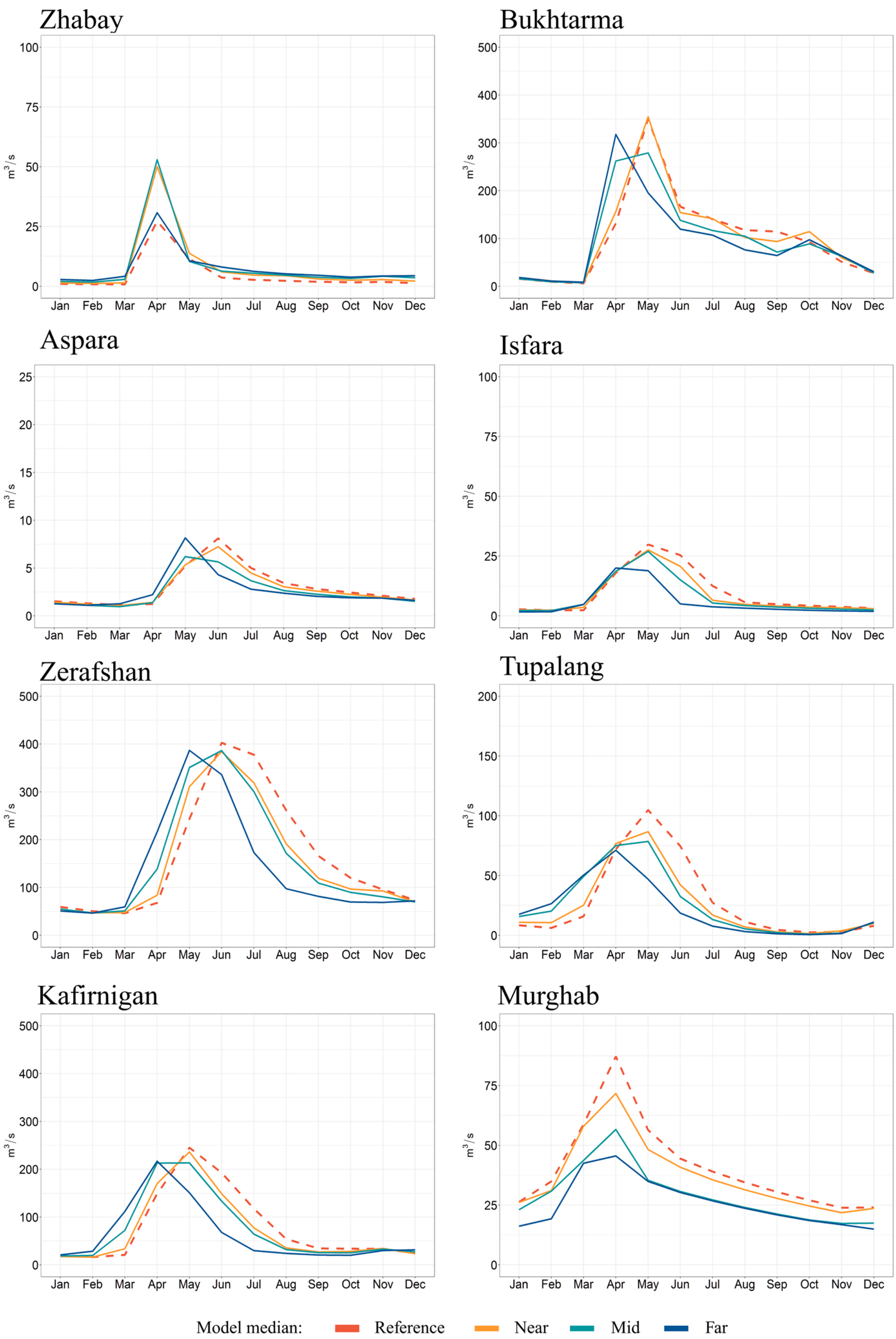

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Fig. 5. Multi-model medians of monthly river discharge for three future periods compared to the reference period under RCP 8.5.

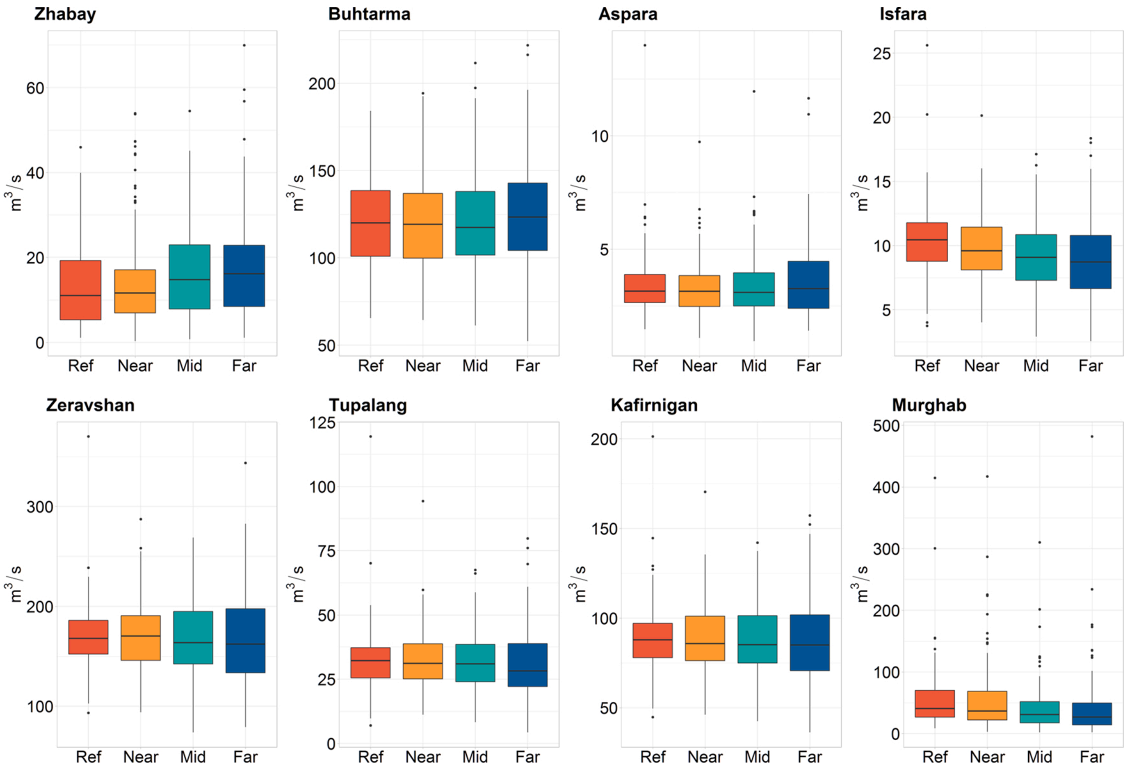

Fig. 6. Box plots of the simulated mean annual river discharge for three future periods compared to the reference period under RCP 4.5 and five climate scenarios. (Upper box lines indicate 75th percentile, lower – 25th percentile, middle – medians, vertical lines show "minimal" and "maximal" values and dots – outliers).

The Central Asian countries are characterized by a low density of the climate station network. Increasing the number of long term meteorological measurements in the region can be helpful to increase the significance of future studies. The river discharge for model calibration was used mainly with the monthly time step, and the daily data were available only for a few catchments, like Bukhtarma, Kafirnigan and Zhabay.

The Central Asian river catchments are mainly driven by snow and glaciers melt, and it is vitally important to consider these processes in the modelling more thoroughly. The SWIM model integrates a snow module and two glacier modules, which allows to improve the modelling of these processes, assuming that observational data is available. The simple glacier module was used in this study instead of the more complex approach mainly due to the lack of observations.

The region is characterized by intensive water management with a dense irrigation network, but because of limited information about water abstraction and reservoir operation, it was not possible to include water management in the modelling. Therefore, only the upper parts of the river catchments, including water accumulation areas, where river runoff is practically not regulated, were considered in this study.

In order to improve the model results and reduce the related uncertainty the following can be recommended for future studies: a) to use better climate projections designed for the Central Asian region; b) to use long time series of climate and hydrological observations together with detailed information on the management practices; c) to implement more precisely the glacier melt process by using observational data and a more complex glacier module; d) to integrate water management in the modelling where necessary.

Besides agriculture, hydropower electricity production is a potentially important sector for the economic development of Central Asian countries, especially Tajikistan and Kyrgyzstan. In this respect, the assessment of climate change impacts on electricity production for the existing and planned hydropower plants is essential for those countries. Another focus can be put on the extreme events, especially on spring floods, which are quite important, for example, for the Zhabay (Kazakhstan) and Kafirnigan (Tajikistan) catchments, as well as for Tajikistan in general.

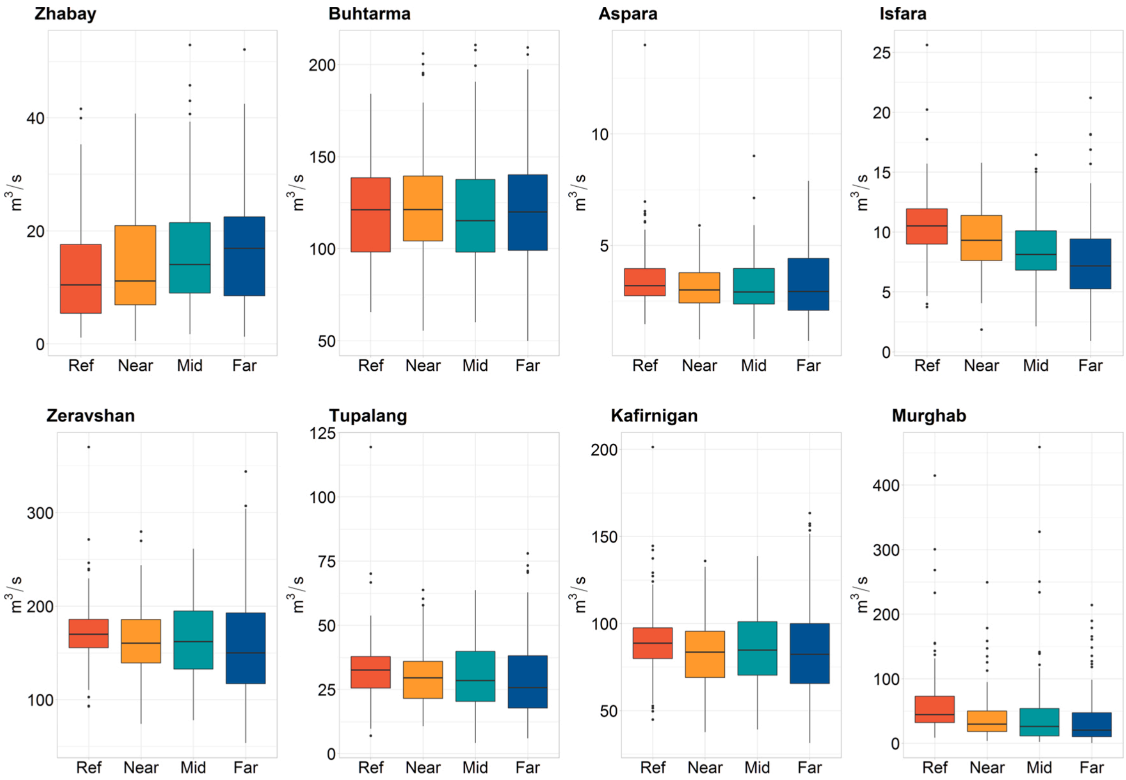

Fig. 7. Box plots of the simulated mean annual river discharge for three future periods compared to the reference period under RCP 8.5 and five climate scenarios (Upper box lines indicate 75th percentile, lower – 25th percentile, middle – medians, vertical lines show "minimal" and "maximal" values and dots – outliers).

6. Conclusions

One of the main issues for societies and economies in Central Asia is water availability. Climate change impact anticipates potential threats and benefits for the socio-economic and environmental sectors. Changes in climate conditions already have an impact on agriculture with a decrease in productivity for water-related sectors (Perelet, 2007). Possible future changes in climate may have serious impacts on natural conditions, water resources and economic development of the Central Asian countries. Therefore, a complex assessment of climate change impacts and adaptation measures is essential for the region.

This study aims to assess potential climate change impacts on water resources in Central Asia by focusing on eight river catchments with diverse natural conditions, and located in different countries. The climate projections show an increase of mean annual temperature in all catchments under both RCP scenarios until the end of the century. Temperature is projected to rise from 3.3 °C to 3.9 °C under RCP 4.5 and from 5.3 °C to 6.4 °C under RCP 8.5 at the end of the century. The highest changes are expected in the Zhabay catchment: up to 6.4 °C under RCP 8.5.

The annual precipitation shows clear trends in two catchments: increase up to 11.5 % in the north (Zhabay), and decrease up to 15.1 % in the south (Murghab) for all periods under both RCPs. In the other six catchments, smaller changes were found. Considering seasonal changes in precipitation, trends are similar to that of annual precipitation: an increase of precipitation in the Zhabay catchment, and a decrease in the Murghab catchment almost throughout the year. The six centrally located catchments have a clear pattern characterized mainly by an increase of precipitation in winter and early spring, and a decrease in summer under both RCPs. The projected changes under RCP 8.5 are more pronounced, and show a reduction of mean monthly precipitation up to 78 % from May to October, except August, in all three future periods considered.

The projected changes in mean annual river discharge for the Zhabay and Murghab catchments are following the precipitation trends. In the Zhabay catchment, river discharge is expected to increase up to 32 % in all periods under both RCPs. In the Murghab and Isfara catchments, river discharge is projected to decrease up to 40 % and 30 % respectively in all periods under both RCPs. For the mountainous catchments, the results show a shift in the peak discharge up to one month earlier, and mainly decrease in summer and autumn months. A shortage of the snow accumulation period and a reduction of the mean annual snowmelt rate were projected, especially at the low altitudes.

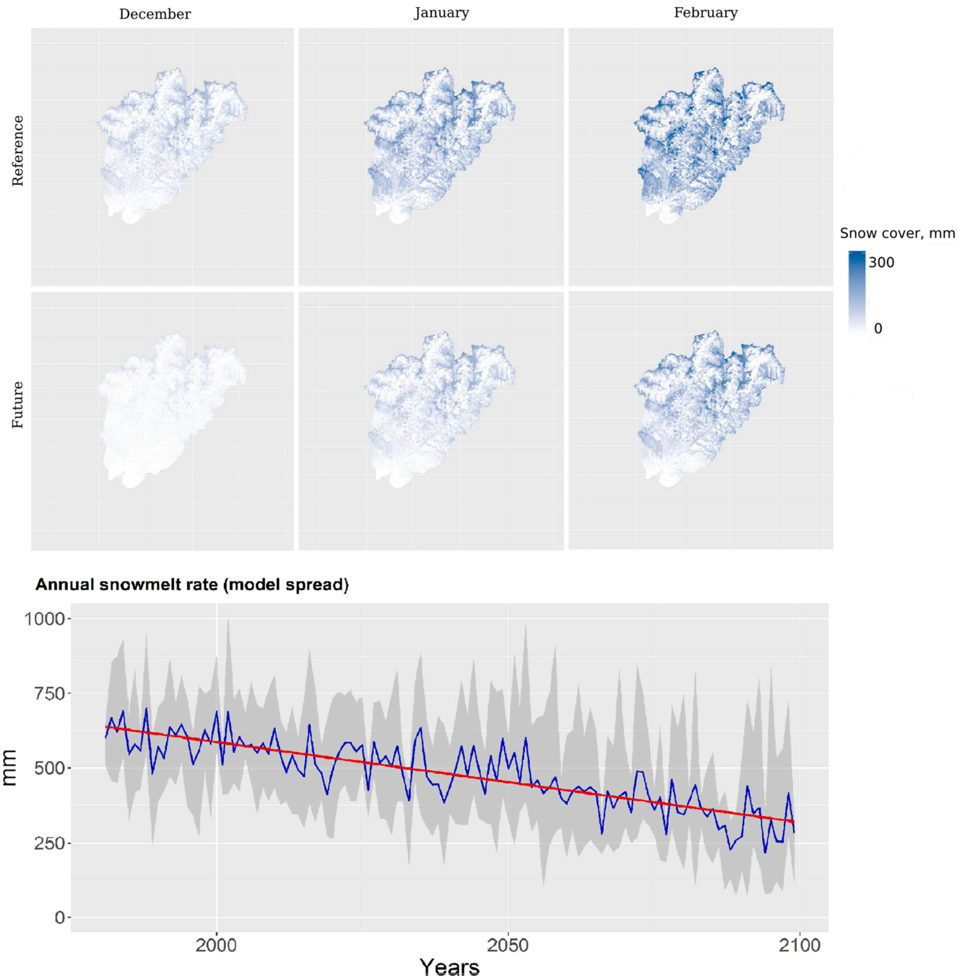

Fig. 8. Mean monthly snow cover in winter months for the reference and future (2071-2100) periods -– upper part; and the multi-model median of annual snowmelt rate – lower part, in the Kafirnigan catchment under RCP 8.5.

The signals of changes found in this study confirm that changes in the hydrological regime are expected in the majority of Central Asian catchments to the end of the century. This is a clear sign of the importance of climate impact assessment for the development of adaptation strategies and cooperation of the Central Asian countries in the climate change context.

CRediT authorship contribution statement

Iulii Didovets: Conceptualization, Methodology, Formal analysis, Writing - original draft, Visualization, Writing - review & editing, Data curation, Investigation. **Anastasia Lobanova:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Data curation, Investigation. **Valentina Krysanova:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Data curation, Investigation. **Christoph Menz:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Data curation, Investigation. **Zhanna Babagalieva:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Aliya Nurbatsina:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Nadejda Gavrilenko:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Vohid Khamidov:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Atabek Umirbekov:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Sobir Qodirov:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Dowletgeldi Muhyyew:** Methodology, Formal analysis, Writing - original draft, Visualization, Investigation, Data curation. **Fred Fokko Hattermann:** Conceptualization, Methodology, Formal analysis, Writing - original draft, Writing - review & editing, Data curation, Investigation.

Declaration of Competing Interest

The authors report no declarations of interest.

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Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:https://doi.org/10.1016/j.ejrh.2021.100779.

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